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STUDY OF UNCERTAINTY IN NOISE MAPPING

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Abstract
Noise mapping is a complex process requiring a large amount of data from different sources, which are not always available. In the process, there are many factors involving simplifications, approaches and deviations that contribute to the final uncertainty of the result. An error in the final result of the noise map causes an incorrect amount of exposed population, as well as the design and implementation of inadequate or wrong noise action plans.
The uncertainty analysis in the creation of noise maps is therefore a key tool to design noise action plans. However, up to now, there are only guides giving an approximate range of possible contribution to the uncertainty depending on the quality of input data.
The present paper analyses the contributions to the total uncertainty of a noise map, proposing a methodology to quantify it. After analyzing the sources that contribute to the overall system uncertainty, a method to quantify the expanded uncertainty properly is proposed, through an analytical calculation and experimental determination. Thus, a specific value of the uncertainty of a map can be calculated avoiding approximations and range values.

Keywords: noise mapping, uncertainty, validation, simulation, measurements.

1 Introduction

Considering the imminent second round of noise mapping and their subsequent 5-year periodic revision [1], the problem of the quality of the maps is set out [2]. The lack of accuracy in noise mapping has a huge repercussion in Noise Action Plans [3], resulting in erroneous figures of people exposed to noise. Based on those wrong figures, measures to decrease noise will be taken with its related economic cost [4].

Present quality requirements of noise maps are not accurateley enough determined due to, among other reasons, the lack of precision in determining the uncertainty contribution of the input data [5]. This paper tries to establish a methodology for a quantitatively determination of the expanded uncertainty of a noise map.

2 Sources of uncertainty in noise maps

Carrying out a noise map by means of simulation techniques and also validated with experimental measurements implies several parameters affecting the final uncertainty.
The main sources of uncertainty of noise maps could be classified in the following groups [5]:

- Experimental measurements.
- Calculation method.
- Calculation engine: software.
- Acoustic model creation.

In a complementary manner, the graphical representation of the maps and the calculation of population exposed to noise can be added as sources of uncertainty to the final results. However, the present paper only studies the uncertainty of the raw output of the simulation, before any interpolation between values for their representation as noise contours.

Similarly, existing methods to determine the amount of population exposed to noise from already calculated levels [6] are not evaluated. Often, the graphical representation and the methods to calculate the spread of errors of the exposed population are usually included in the calculation and the computer model. Additionally, human errors in the data processing in the entire development of a noise map may occur as they need a large amount of data, formats, conversions and origins of the same [7].

3 Uncertainty calculation methods

The problem of the spread of uncertainty is called *distributions spread* and there are several techniques to deal with it [8]:

- Use the Guide to the Expression of Uncertainty in Measurement (GUM) [9] by applying the uncertainty propagation law and the characterization of the final variable using a Gaussian distribution or a t-distribution function.
- Mathematical analytical methods to determine the probability distribution of the variable Y (variable related to simulation factors).
- Monte Carlo Method (MCM), which comes to an approximation of the probability distribution of the variable Y, by means of input variables random values evaluating the results of the model output.

Apart from the techniques proposed by the GUM, there is the *fuzzy logic*, which defines values in a real closed interval and applies functions with real numbers to its extension with *fuzzy numbers* [10]. The biggest problem of fuzzy logic as a tool to determine the uncertainty is the computational cost and complexity; however, it delivers results more quickly than other methods [11].

With regard to the analytical methods they have a difficult implementation when entailing many variables and there is no information about all of them or their probability density function (*pdf*) [12, 13]. In the case of noise maps, where there are more than 40 variables affecting the expanded uncertainty they have not been characterized enough to perform an uncertainty analysis. Even on this premise, certain data related to a noise map (geometrical data) could throw an approximation of its contribution to the total uncertainty through analytical methods [14].

Therefore, MCM is the perfect method to quantify the uncertainty related to a noise map based on their input data [15]. Consequently, MCM has been the method used by the GPG to determine the uncertainty ranges associated with each input data based on its quality. However, the MCM provides results approximate to the exact results that might provide an analytical method [16].

The uncertainty ranges associated with the quality of the data in the GPG are not precise at all, and they have been classified into the following groups:

- Less than 0.5 dB.
- Between 0.5 and 1 dB.
- Between 1 and 3 dB.
- Between 3 and 5 dB.
- Greater than 5 dB.

In addition, the real utility of the uncertainty related to a unique input data, without knowing its contribution to the expanded uncertainty of the complete map is scarce. So there is a real need to determine quantitatively the expanded uncertainty of the outcome of a noise map.

4 Measurement uncertainty calculation

Although there are several methods, guides, approaches and recommendations to determine the uncertainty of the noise level measurements [17-21], authors have chosen to use the updated GUM [12], as it is the policy document for that purpose. As stated on that document, the uncertainty of measurement consists of category A and category B contributions.

$$Y_M = f\ (X_{MA}, X_{MB}) \tag{1}$$

Where:

- X_{MA}: Category A contributions, due to random variable measurement (noise).
- X_{MB}: Category B contributions, due to the equipment used.

$$X_{MA} = f\ (X_{MA1}, X_{MA2}, X_{MA3}, \dots, X_{MAn}) \tag{2}$$

Where:

- X_{MA1}: Variability of noise source.
- X_{MA2}: Measurement lenght.
- X_{MA3}: Number of samples.
- Etc.

$$X_{MB} = f\ (X_{MB1}, X_{MB2}, X_{MB3}, \dots, X_{MBn}) \tag{3}$$

X_{MBn} contributions are due to: Resolution, Calibration, AC circuits, A-Weighted filters, linearity, attenuator, RMS, environmental Kit and environmental conditions, among others [22].

The methodology proposed by the GUM consists on calculating separately the categories A and B uncertainties in order to calculate the combined uncertainty subsequently. Thus, the Type A or standard uncertainty u (L) can be determined as follows [12]:

First, the variance $s^2(L)$ is defined:

$$s^2(Li) = \frac{1}{n-1}\sum_{i=1}^{n}(L_i - \overline{L})^2 \tag{4}$$

Where:

- n is the number of samples.
- L_i are the Noise Levels samples.
- $\overline{L}$ is the mean Noise Level.

Then, the variance of the mean is calculated, $s^2(\overline{L})$:

$$s^2(\overline{L}) = \frac{s^2(Li)}{n} \tag{5}$$

Finally, Type A standard uncertainty, u(L), can be defined from the measurement standard deviation:

$$u^2(L) = s^2(\overline{L}),\ \text{or: } u(L) = s(\overline{L}) \tag{6}$$

To calculate the Type B standard uncertainty, as established before, previous data, other instruments analysis, manufacturers data, calibration laboratories and reference manuals and books were consulted [17, 18, 23, 24]; identifying the most important contributions due to the equipment. Once the contributions to the uncertainty of each factor are established, the Type B uncertainty u(E) [12] can be determined in the following way:

$$\mathrm{u(E)} = \sqrt{\sum \delta_i^2} \quad (7)$$

Where:

δ_i All the contributions to the uncertainty due to corrections and calibrations previously described.

In order to calculate the combined uncertainty (u_c) due to Type A and Type B contributions, the following equation is used [12]:

$$\mathrm{u_c^2} = \mathrm{u^2(L) + u^2(E)};\ \text{or: } u_c = \sqrt{\mathrm{u^2(L) + u^2(E)}} \quad (8)$$

Finally, to determine the expanded uncertainty (U), the combined uncertainty (u) is multiplied by the cover factor (k). Following the GUM recommendations, a cover factor k=2 has been used, assuring the value is included in the uncertainty with a probability of 95.45% [12]. So, the expanded uncertainty (U) is expressed as follows:

$$U = u_c \cdot k;\ \text{at the present research: } U = u_c \cdot 2 \quad (9)$$

5 Uncertainty calculation method proposed

The uncertainty propagation model related to a noise map [5] considers both measurement contributions (Y_M) and simulation process contributions (Y_S).

$$Y_S = f\ (X_{SA}, X_{SB}, X_{SC}) \quad (10)$$

Where:

- X_{SA}: Contributions related to the acoustic calculation method choosen.
- X_{SB}: Contributions related to the calculation engine used.
- X_{SC}: Contributions related to the creation of the acoustic model.

And:

$$X_{SA} = f\ (X_{SA1}, X_{SA2}, X_{SA3}, \dots, X_{SAn}) \quad (11)$$

Where:

- X_{SA1}: Vehicles categorization.
- X_{SA2}: Speed dependence.
- X_{SA3}: Porosity influence.
- Etc.

$$X_{SB} = f\ (X_{SB1}, X_{SB2}, X_{SB3}, \dots, X_{SBn}) \tag{12}$$

Where:

- X_{SB1}: Calculation model implementation.
- X_{SB2}: Searching radius.
- X_{SB3}: Number of reflections.
- Etc.

$$X_{SC} = f\ (X_{SC1}, X_{SC2}, X_{SC3}, \dots, X_{SCn}) \tag{13}$$

Where:

- X_{SC1}: Traffic data.
- X_{SC2}: Environmental conditions.
- X_{SC3}: Cartography.
- Etc.

Therefore, the total simulation result could be expressed as a function of all the variables mentioned above:

$$Y_S = f\ (X_{SA1}, X_{SA2}, X_{SA3}, \dots, X_{SAn}, X_{SB1}, X_{SB2}, X_{SB3}, \dots, X_{SBn}, X_{SC1}, X_{SC2}, X_{SC3}, \dots, X_{SCn}) \tag{14}$$

Having a complex variable composed by such a large number of single variables, the *central limit theorem* could be applied, obtaining a Gaussian distribution [25, 26].

In this way, the uncertainty calculation method laid down in the GUM can be used; so the final variable (Y_T), which is the total uncertainty of the noise map process, can be expressed as a function of two independent variables: Measurement contributions (Y_M) and Simulation contributions (Y_S).

$$Y_T = f\ (Y_M, Y_S) \tag{15}$$

By means of this method, the total uncertainty calculation process can be simplified and cuantitatively determined (Fig. 1).

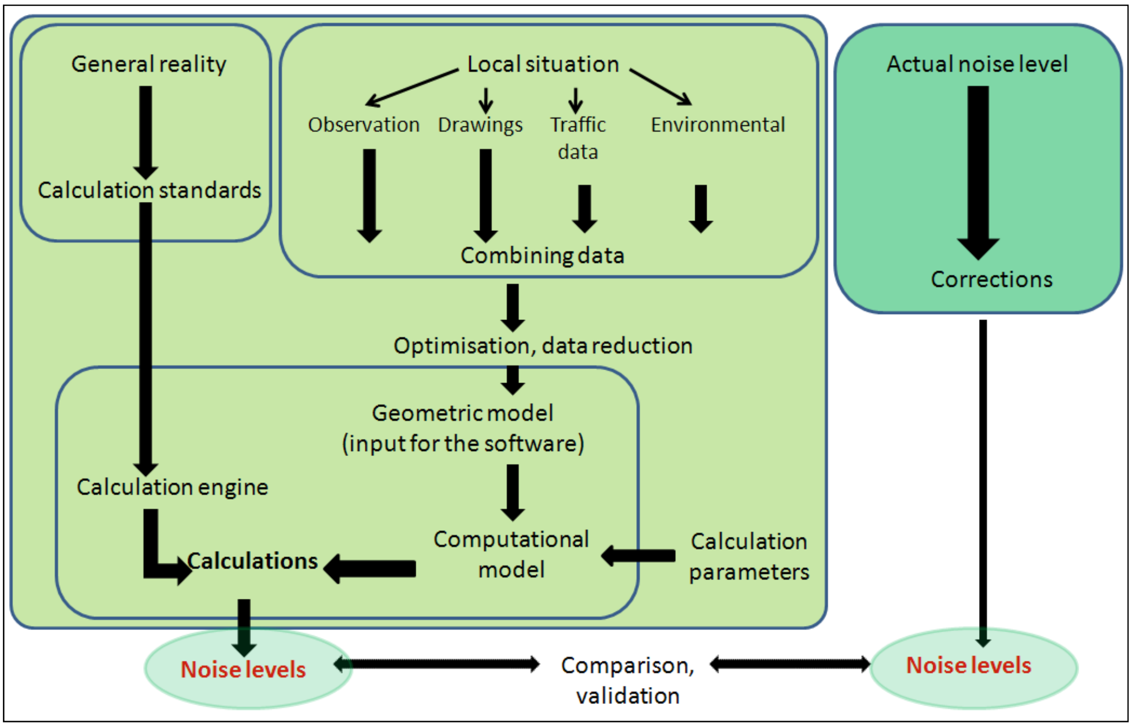

Figure 1 – Uncertainty contributions simplification.

In order to calculate the combined uncertainty, the uncertainty propagation law was applied, assuming that all the input data are independent variables, so their correlation coefficients are null [12].

In addition, contributions to the uncertainty of the calculation engine have been reduced, maximizing the simulation time by means of the calculation parameters [27]. Thus the uncertainty from the input data and the creation of acoustic model charge more weight in the contribution to the total uncertainty.

Consequently, 3 hypotheses can be raised:

- Hypothesis 1: If the measurement process has a null expanded uncertainty or absolutely negligible, the total expanded uncertainty determined by the validation process would have only simulation process contribution.
- Hypothesis 2: If the simulation process has a null expanded uncertainty or absolutely negligible, the total expanded uncertainty determined by the validation process, would correspond exclusively to measurement process.
- Hypothesis 3: If the measurement and simulation processes have associated expanded uncertainties, the total expanded uncertainty determined by the validation process will be a function depending on both contributions.

The total expanded uncertainty of the map, will be determined empirically using a coverage factor k = 2, and therefore the likelyhood that data have a less than 95.45% dispersion, as shown in Fig.2.

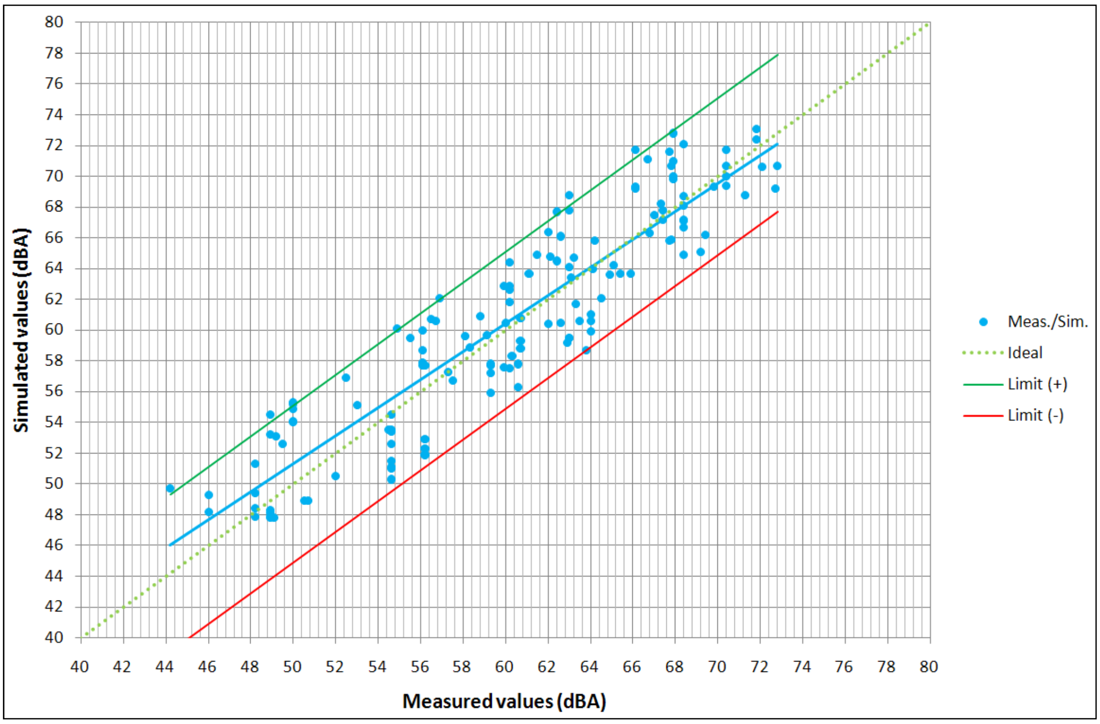

Figure 2– Example of the expanded uncertainty empirically determined [28].

Given that the combined uncertainty of the measurement process (and therefore the expanded uncertainty), can be analytically calculated and the total expanded uncertainty of the entire process is empirically determined depending on the coverage factor established (k); the expanded uncertainty due exclusively to the simulation process can be calculated using the following equations:

$$U_T = u_{cT} \cdot k \tag{16}$$

$$u_{cT} = \sqrt{\mathrm{u}^2(\mathrm{M}) + \mathrm{u}^2(\mathrm{S})} \tag{17}$$

$$u(S) = \sqrt{{u_{cT}}^2 - \mathrm{u}^2(\mathrm{M})} \tag{18}$$

$$U(S) = u(S) \cdot k \tag{19}$$

Where:

U_T is the total expanded uncertainty of the noise map, empirically determined (Fig. 2).

u_{cT} is the total combined uncertainty of the noise map, calculated from U_T.

u(M) is the combined uncertainty due to measurement process, analytically determined.

u(S) is the combined uncertainty due to simulation process, calculated from u_{cT} and u(M).

U(S) is the expanded uncertainty due to simulation process, calculated from u(S).

6 Conclusions

The present paper analyses the contributions to the total uncertainty of a noise map, proposing a methodology to quantify it. Firstly, a review of the state of the art is performed, studying different aspects contributing to the system uncertainty: calculation standard, acoustic calculation engine, situational acoustic model and acoustic measurements. After analyzing the sources that contribute to the overall system uncertainty, a method to quantify the expanded uncertainty properly is proposed, from an analytical calculation and experimental determination. Thus, a specific value of the uncertainty of a map can be calculated avoiding approximations and range values.

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